Issues and Concepts for Making Durable Composites

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ABSTRACT

Perhaps the greatest obstacle facing the acceptance of engineered wood composite products into new markets is the perceived lack of durability. Public perception is that particleboard and other wood-based composites fall apart when exposed to water. This paper will review the unique characteristics of wood-based composites that make them more or less susceptible to durability-related problems. Some aspects of chemical and thermal treatments relative to composite durability will also be discussed. Emphasis will be placed on adhesion and interactions with water.

Keywords *Wood composites, engineered composites, durability, treatments, dimensional stability*

INTRODUCTION

A definition of durability would be helpful for this discussion. Jay Johnson (1984) once stated "the durability of a product is an attribute related to the time taken for it to degrade to the point where it fails to perform its intended purpose or function." Since there are many "functions" for wood products, the important "attribute" may not be the same for all products. For example, thickness swell of an OSB siding product is a critical attribute, while thickness swell of a stud within a wall is of little consequence. The stud can swell, yet still perform the structural support function needed for the building. Swelling of the siding product may cause the paint film to fail or perhaps the swelling may cause an uneven appearance of the exterior wall – consequently the aesthetic function of the siding will be compromised. On the other hand, the growth of wood decay fungi should be of concern for all wood product applications, since usually nothing good will come of it. The factor of "time" is often neglected in discussions of durability. Often wood products are only exposed to a hazardous condition (water) for a finite, sometimes even a brief period of time. The level of protection, and associated cost, should be appropriate for the expected duration of exposure. Finally, the term "degrade" could refer to loss of wood mass due to fungal or insect activity; or degrade could refer to loss of mechanical integrity due to irreversible moisture-induced swelling due to release of residual compressive stress left-over from hot-pressing with some subsequent failure of adhesive bonds; or degrade could be associated with some esthetic quality important to the performance of the product. Any assessment of durability must be specific to the product and its application.

Experience has shown that wood composite products tend to behave differently than solid-sawn wood upon exposure to water. A loss of product performance due to attack by fungi or insects is often perceived to proceed more rapidly in a wood composite. This paper will review the unique characteristics of wood-based composites that make them more or less susceptible to durability-related problems. Emphasis will be placed on adhesion and interactions with water. Some implications of chemical or thermal treatment on composite durability will also be discussed.

DISCUSSION

Is wood wood?

Wood is wood, so why should one expect any difference in regard to durability between solid-sawn wood products and wood composites? From the standpoint of the ability of the cells within the wood to absorb water or provide a food source for fungi and insects, there is little or no difference. However, certain details in how the wood is first reduced to a furnish, and then put together as a composite, can often greatly influence their susceptibility to deterioration. A list of factors that lead to the unique durability behavior of wood composites is shown below.

Smaller pieces of wood	Adhesive / other additives
Multiple species	Uniformity
Less decay resistant species	Lack of defects
Grain orientation or lack of it	Dimensional stability
Voids	Secondary processing
Density	Dimensions of products
Temperature exposure	Product applications
Residual stress from pressing	Variable vertical density profile

Composites are made from small pieces of wood (Figure 1). Each wood composite product has a unique materials composition and lay-up and performance attributes (Figure 2). These wood elements may be individual wood cells or cell fragments, such as found in fiberboard products. The wood elements may be thin sheets of veneer, such as found in plywood and laminated veneer lumber. Some decorative veneer is less than 0.5-mm thick, while core stock in some structural plywood grades may be as thick as 6 mm. Particleboard is made from particles of varying sizes and shapes – from sander dust to planer shavings. Oriented strand board (OSB) is made from strands of dimensions roughly 0.6 mm by 8-25 mm by 75-150 mm. All of these wood elements are combined with adhesive, assembled into a mat or billet, and compressed at 130-220°C into a sheet ranging from approximately 5 to 30 mm in thickness. Other composites include structural composite lumber products, such as laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL). LVL and PSL are produced from veneer, while LSL is made from strands. The structural composite lumber products have many similarities to composite panels, but they are thicker products with different applications.

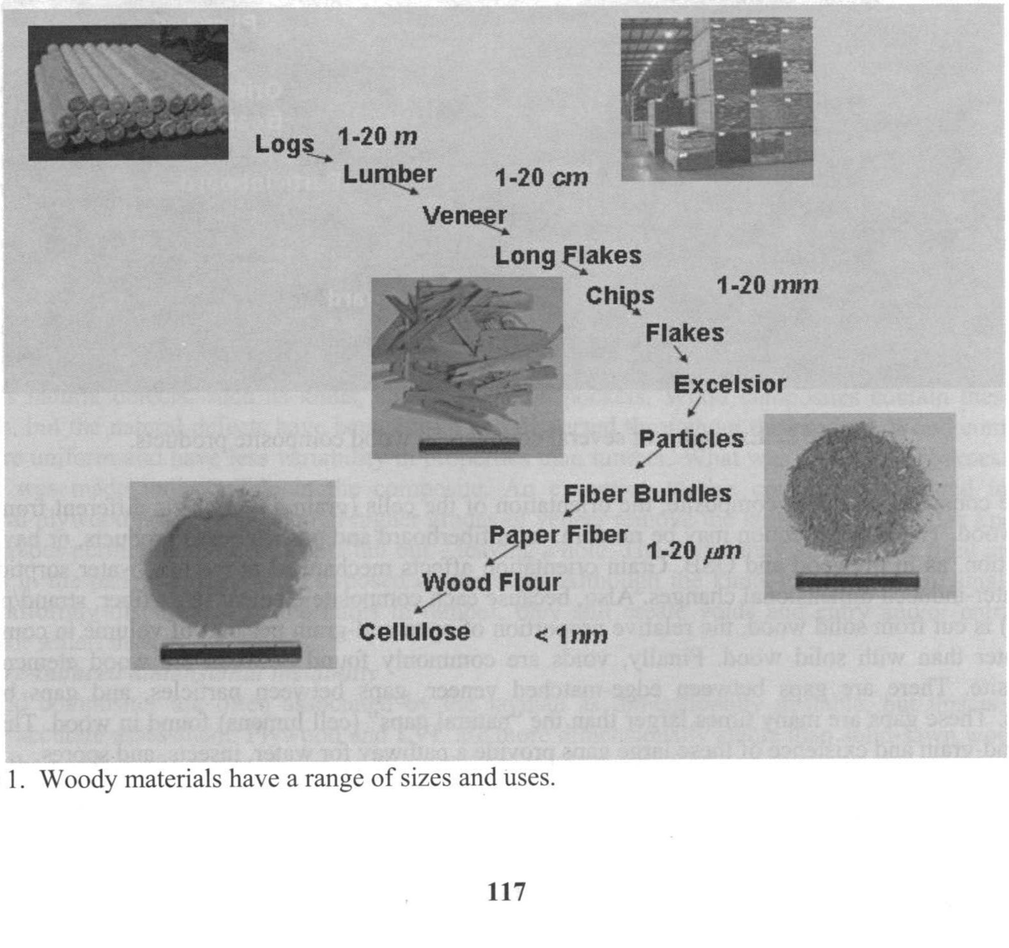

Figure 1. Woody materials have a range of sizes and uses.

During the process of manufacturing composites the surfaces of the wood elements are exposed to the surrounding environment, including fungal spores and insects. In the case of wood residues from other manufacturing processes, there may be a delay of several weeks before the material is processed. Chip piles are often stored outdoors. Particleboard and fiberboard products utilize wood residues. Veneer composites, OSB, and LSL begin the manufacturing process with logs, and in this regard the material handling is not significantly different than a sawmill. However, one could argue that there is a large difference in log quality and wood species delivered to a typical composites mill as opposed to those delivered to a sawmill.

The wood used to manufacture a single composite may come from many species. It is not uncommon to find hardwoods and softwoods mixed in the same sheet of plywood or OSB. Some OSB mills routinely use over 20 species. Each species has its own natural resistance to biological decay and each species will adsorb water at a different rate. Unfortunately, some of the most common species used for structural panel products have the least natural resistance to decay. Aspen, yellow-poplar and southern pine are the dominate species use to manufacture OSB in North America, yet they are among the least decay resistant species (USDA 1999). While some of the southern pine species have moderate heartwood decay resistance, the small diameter or rapidly-grown logs that are frequently processed for structural composites have only a small proportion of heartwood. Further, for plywood most of that heartwood is never peeled into veneer and ends up in the peeler core.

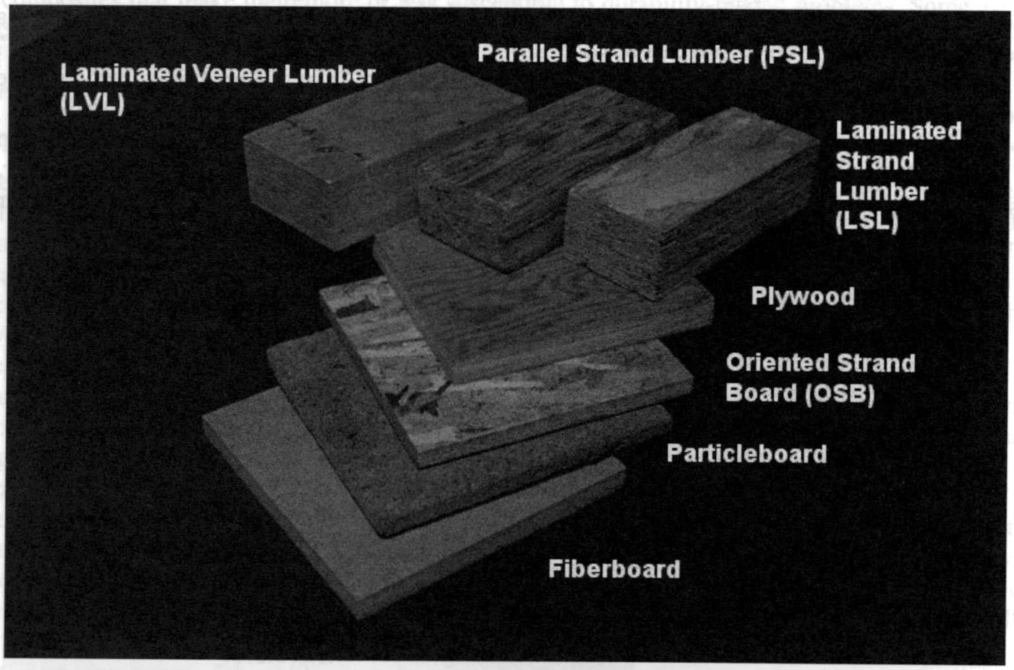

Figure 2. Examples of several commercial wood composite products.

Once consolidated into a composite, the orientation of the cells (grain direction) is different from solid-sawn wood. The grain direction may be random, as in fiberboard and particleboard products, or have some orientation, as in plywood and OSB. Grain orientation affects mechanical properties, water sorption rate, and water-induced dimensional changes. Also, because each composite element (e.g., fiber, strand/particle, veneer) is cut from solid wood, the relative proportion of open end-grain per unit of volume in composites is greater than with solid wood. Finally, voids are commonly found between the wood elements in a composite. There are gaps between edge-matched veneer, gaps between particles, and gaps between strands. These gaps are many times larger than the "natural gaps" (cell lumens) found in wood. This more open end-grain and existence of these large gaps provide a pathway for water, insects, and spores.

Influence of density

With the exception of insulation board, all composites have a greater density than the solid wood from which it was made. Most composites require some type of adhesive bonding. Adhesive bonding requires surface contact. In an effort to create surface contact, the mat or billet of wood elements must be compressed. Usually this is accomplished in a heated hydraulic press. The particles, fibers, strands or veneers have enough irregularity to prevent a perfect match, thus the wood elements must be compressed beyond their natural density to create adequate compressive stress to promote adhesive bonding. The result is a composite that is 5% (for plywood) to over a 100% (for hardboard) greater in density than the solid wood from which is was made. The OSB manufacturing process typically results in 50% increase of density, including the encased voids between the strands. The significance of higher density is greater potential for thickness swelling of composites. Furthermore, much (often most) of the thickness swell is not reversible with a subsequent loss of structural integrity due to release of some residual compressive stress from hot-pressing. Therefore, one swelling cycle opens more void space, such that future exposure to water will occur more rapidly. This affect is normally not a significant problem with plywood and LVL, but is a serious concern for OSB, SCL, particleboard, and fiberboard products. The use of highly water resistant adhesives and higher adhesive content will significantly reduce, but not eliminate, this problem.

Adhesives and additives

With few exceptions, all wood composites require adhesives. There are too many different types and formulations of adhesives used by the wood composite industry to make many broad generalizations. All of these adhesives are thermosets, which means they polymerize and cross-link when they cure. Exposure to high temperature accelerates the cure of a thermoset adhesive. Urea-formaldehyde adhesives, which are typically used for particleboard and interior plywood grades, have little resistance to moisture. Phenol-formaldehyde and isocyanate (also referred to as MDI) adhesives, which are typically used in structural panels and structural composite lumber products, have very good resistance to water. None of these adhesives are susceptible to decay fungi or insects, but neither do any of them impart any significant decay resistance to the wood elements. Moisture cycling of the composite causes additional stress on the adhesive bond as the wood swells and shrinks. Eventually some of the adhesive bonds fail, which may lead to more swelling, more gaps between the wood elements, and certainly a loss of structural integrity. Again, the use of highly water resistant adhesives and higher adhesive content will significantly reduce, but not eliminate, this problem.

Other chemical additives may be blended with the wood elements during manufacture, some of which will impact durability. Wax is added to fiberboard, particleboard, and OSB products to improve short-term resistance to liquid water. These waxes have no affect against water vapor and do not prevent water intrusion over the long-term. Some commercial products include biocides and fire retardants. In any case, these additives must be compatible with the adhesive system used. A standardized test of compatibility would be beneficial.

Natural defects

Product uniformity and the existence of defects are characteristics that distinguish solid-sawn wood from wood composites. With the exception of the very highest appearance grades of lumber, solid-sawn wood contains natural defects, such as knots, splits, and pitch pockets. Wood composites contain these same features, but the natural defects have been cut-up and dispersed throughout the product. Wood composites are more uniform and have less variability in properties than lumber. What was a point of weakness in the lumber was made indiscernible in the composite. An exception to this conclusion is found in many structural plywood products. Although higher grades of veneer remove the large knots and open knots, the lower grades permit them. Loose knots fall out – leaving a hole. The knots are visible on the front and back veneers in the panel, and are often exposed on the edge. Although the knots in plywood are smaller and more uniformly dispersed than the knots in lumber, they still create voids and entry and/or entrapment points for water, insects, and spores.

Moisture-induced dimensional instability

Wood composites are often associated by the layman as dimensionally unstable, but this is not an entirely accurate assessment. Plywood and LVL are more dimensionally stable than solid-sawn wood. The greater the number of veneers, the more stable the panel will be. Solid-sawn wood must contend with the growth-ring orientation. Flat-sawn lumber is notorious for warping upon a change of moisture content.

Lumber also shrinks and swells about 25-50 times more (percentage basis) in width and thickness (radial and tangential direction) than length (longitudinal direction) (USDA 1999). The cross lamination in plywood provides mechanical restraint in the width and length; thus dimensional changes in length and width are essentially equal and relatively uniform. For structural plywood and LVL, the thickness direction is always the radial direction, which has a maximum water-induced dimensional change of 5% or less. The tangential direction in lumber may shrink or swell as much as 11% (USDA 1999). However, in our experience fiberboard, particleboard, and OSB panels are more dimensionally stable in length and width compared to the width and thickness of lumber. This stability for composite panels is related to the uniform density variation from face-to-core-to-face across that length and width creating a laminated-like construction in many ways similar to plywood and LVL.

Where products like fiberboard, particleboard, and OSB suffer is thickness swell. Even when a highly water resistant adhesive is used, thickness swell in these products will be greater than lumber. A thickness swell of 25% after 24 hours of water exposure is common for OSB, with greater swelling at the edges of the panel (when compared to middle of panel) the greatest concern to users. This problem has long been recognized by the industry, so edge-sealants are often applied to OSB products. As previously mentioned, much of the thickness swell will not be reversible upon loss of water. One must also consider the implications to performance and utility related to this differential rate of swelling when the wood composites are exposed to water. Because the density of the composite is generally high, the adsorption rate is slower than solid-sawn wood. In addition, due to the high temperature exposure during processing and the presence of wax in some of these products, the composite will for a short time actually repel liquid water. However, given time, significant thickness swell should be expected.

High-temperature exposures in processing

During composite manufacture the wood elements are exposed to high temperature not typically used in the manufacture of lumber – in particular the two processing steps are: 1) preparation and drying of veneer, particles, fiber, or strands and 2) hot-pressing. Veneer dryers typically operate in the range of 150 to 200°C, although the veneer is exposed to this condition for only 10 to 15 minutes. Strand dryers have been known to operate with an inlet air temperature of over 600°C, but the wood is exposed for only a few seconds. Hot-press temperature ranges from 130 to 220°C depending on the adhesive type and product thickness. The high temperature exposure in composite processing does promote some limited phytosanitation, although there isn't much data available on the interaction of time and temperature. For most instances, it is not very probable that composite processing temperatures (90-125°C) for 3-5 minutes can fully sterilize wood fibers. Experience has shown that higher than atmospheric pressure and longer durations are required when autoclaving (121°C, 15 psi, 15 min) to kill spores (ASTM D1413). While boiling water/steam kills most vegetative bacterial and fungal hyphae in minutes, bacterial and fungal spores are often not killed, even after hours of boiling.

Other considerations of wood composites

Because of the versatility of composite products, there are numerous secondary processing operations that have an impact on durability. Edge and surface sealants are commonly applied on structural sheathing and, sometimes, to structural composite lumber products. Surface overlays, including resin-impregnated paper, vinyl foils, and other materials, are used for applications where frequent liquid water exposure is expected. Many composite products are pre-primed with a coating before leaving the manufacturing facility.

While structural composite lumber products have similar shapes and sizes to their solid-sawn counterparts, composite panels differ greatly. Because of their intended function, panel products are thin and wide. Water has a very short distance to penetrate completely into a thin composite panel. A decay zone of 2 mm in a 12 mm thick panel is more significant than 2 mm in a 38 mm thick structural lumber product. Sheathing products protect what is underneath or they provide a platform upon which other components are built. The sheathing is usually the first line of defense against the elements of deterioration if the cladding and/or drainage system(s) fail to function properly. If a deterioration problem is to occur, it often is first revealed in the sheathing before the lumber products underneath are affected. This doesn't mean the sheathing was necessarily less durable, but rather it was exposed to more severe conditions and for awhile it protected the structural framing.

Chemical treatment

There are many factors that may impact the durability of wood composites. In some cases composites are inherently at a disadvantage in comparison to solid-sawn wood. However, composites offer many opportunities to engineer properties, including the properties that define durability.

Pressure-treated plywood, LVL, and PSL are commercially available. A number of post-manufacturing pressure treatments have been developed for composites using various preservative systems (Commodity specification F: wood composites, Standard U-1, AWPA BOS 2007). As a practical general rule, with few exceptions, laminated composites such as plywood, laminated veneer lumber and parallel strand lumber can be pressure-treated after manufacturing. This ability to withstand the physical rigors of the pressure-treatment process probably relate to their use of thicker (>1 mm) veneers or clipped veneer strands which in turn produces a composite based as much on wood properties as wood-adhesive bonding. Conversely, except for non-swelling or vapor-based chemical systems, composite products such as oriented strand board and structural composite lumber can not usually be pressure treated because of the thinner strands (<1 mm thick) used as a base material. These thinner strands absorb water and swell to such a degree that too many wood-adhesive bonds are permanently broken and irreversible swelling and loss in strength occurs. Development of practical, economical, non-volatile, and non-swelling chemical systems holds value as a future direction for producing durable composites (Laks 1999, Winandy 2002).

The many steps in the composite manufacturing process offer several options for introducing chemical treatments. The wood elements may be treated with preservative, fire-retardant, or water-repellant chemicals prior to blending with adhesive, simultaneously with adhesive, after blending with adhesive, or the composite product may be treated after it is manufactured. In some cases these chemicals may be included in an adhesive formulation and simply applied without any changes to the normal composite manufacturing process. The advantage of treating the wood elements prior to composite manufacture is small size and ready availability of endgrain for chemical penetration. However, the large variation in large-to-small size of wood particles or strands present difficulty in that smaller particles often absorb significantly more chemical (e.g., adhesive resin, wax, or preservative) than the large particles, thus uniformity of chemical application is difficult. In addition, the chemical nature of the treatments may interfere with adhesive cure and bonding.

Pressure treatment of composite products with waterborne chemicals is usually not suitable for particulate wood composites, because as has been discussed the water causes irreversible swelling, and often a severe loss of structural integrity for the composite. Veneered composites, such as plywood and LVL bonded with a moisture resistant adhesive, can be pressure treated and re-dried without significant loss in properties. This is also true of PSL, which is also a veneer-based composite even though the name would imply it's made of strands. Solvent-borne pressure treatments may be used that do not cause excessive swelling (Smith and Wu 2005). However, this process is expensive and requires solvent recovery.

Integral process treatments have been developed for use with particulate composites (Barnes and Kirkpatrick 2005, Bender et al. 2002). In this case the preservative chemical is added simultaneously in the resin blender or pre-mixed with the resin or wax. Advantages to this approach are homogeneous distribution of active chemical, selective loading levels in specific layers, reduced processing cost, and the ability to machine the composite without loss of protection (Manning 2002). Integral treatment methods must allow for controllable flow properties of the resin or wax system, thermal stability in the hot-press, low volatility, low interaction with adhesive bonding, and minimal in-plant environmental hazard. Thermal stability of the active biocide is particularly critical with all treatments that occur prior to the hot-press. Hot-press temperature, depending on the adhesive type, will vary from 130 to 220^{o}C, with a press time of perhaps 3 to 10 minutes.

In-line chemical treatments to enhance durability which are fully compatible with commercial composite-manufacturing technology have been extensively studied for several decades by composite researchers (Goroyias & Hale 2004, Hall et al 1982, Laks & Palardy 1991, Schmidt & Gertjejansen 1988, Schmidt 1991, Vick et al 1990). Significant work has shown that borate-based chemical systems are highly adaptable to particle-, fiber- or strand-based composites because of its compatibility with traditional adhesive resin systems (Hsu & Pfaff 1993, Knudson 1990, Laks and Palardy 1990, Lee et al 2001, Myles 1994, Sean et al 1999).

Vapor-based systems have also been studied but not yet commercialized (Barnes and Amburgey 1993, Bergervoet et al 1992, Hashim et al 1992, Hirano et al. 2004, Jones et al 2001, Murphy 1994, Vinden et al 1991). Other copper-based preservative systems for in-line composite processing have also been developed and commercialized (Nieh et al 2004). Still other fire-retardant chemical systems have been investigated as in-line processes (Ayrilmis et al 2004, Winandy et al 2008).

Thermal treatments

It has been shown that even a short-term exposure to high temperature reduces the ability of wood to adsorb water and this can dramatically affect composite durability. Upon extended high-temperature exposures in hot presses both Militz (2008) and Winandy & Krzysik (2007) found that extended heat-treatment during the pressing process for engineered wood composites improved water-resistance and limited thickness swell. But, while this is good to a degree, excessive thermal exposure of wood may make the wood elements difficult to bond with water-borne adhesive systems (Christiansen 1990 and 1991; Sernek et al. 2004).

OPPORTUNITIES

Considerable work has been done on using heat treatments to modify the wood as a means to enhance durability (Antoine et al 1971, Brauns and Strand 1959, El'bert 1962, Goroyias and Hale 2002, Liiri 1969, Suchsland and Enlow 1968, Winandy and Kryzsik 2007). This process can be accomplished at various stages in the composite manufacturing process such as in particle/flake drying, hot-pressing or post-pressing operations. The advantage is that the material is both preservative-free and moisture resistant; the drawback is that the processes are energy consuming and often significantly slow composite processing.

Innovative non-toxic treatments have also been developed. For example, acetylation of wood fiber may be performed prior to mat formation. This is a continuous process, including a chemical recovery step, that completes the acetylation process prior to blending the treated fiber with phenol-formaldehyde or pMDI adhesive (Rowell and Simonson 2004; Hirano et al. 2004). Acetylation of wood composites has received little attention as a commercial venture in North America, but it has recently been commercialize in Europe. It does present challenges for adhesive bonding, but experiences with fiberboard would indicate that these challenges can be overcome (Rowell et al 1988)..

SUMMARY

While solid-sawn wood and timber represent a quasi-steady market, the wood composites market is fast growing. Yet the Achilles heal of composites is durability. Enhancing the durability of a generally less-durable material than solid-wood is important to continued market expansion. If consumer expectations for comparable durability to that of solid-wood continue, eventually the long-term durability of wood composites will be a primary factor that decides whether the past market trend continues or ebbs. Thus, it is in the best interests of the entire wood protection community to develop the systems and process technology for enhancing the durability of wood composites. These materials are not the same as solid-sawn wood; therefore one should not expect conventional wood protection technology to yield the same results.

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